Cosmic Microwave Background

A Prelude

- In 1940s George Gamow, Ralph Alpher, and Robert Herman studied the creation of chemical elements (process of *nucleosynthesis*) in the early universe.
- They found out that the early universe had to be hot, otherwise all the matter in the universe would have turned into helium gas.

Question

- What does hot gas do?
  A. Grows
  B. Glows
  C. Goes
  D. Gnaws
  E. Evaporates

A Prelude

- That hot universe would be filled with the glow of the hot gas – we call it now Cosmic Microwave Background radiation.
- They also predicted the Cosmic Microwave Background radiation should have temperature today of about 5 degrees Kelvin (the true number is 2.73K). This work was largely forgotten (until recently).

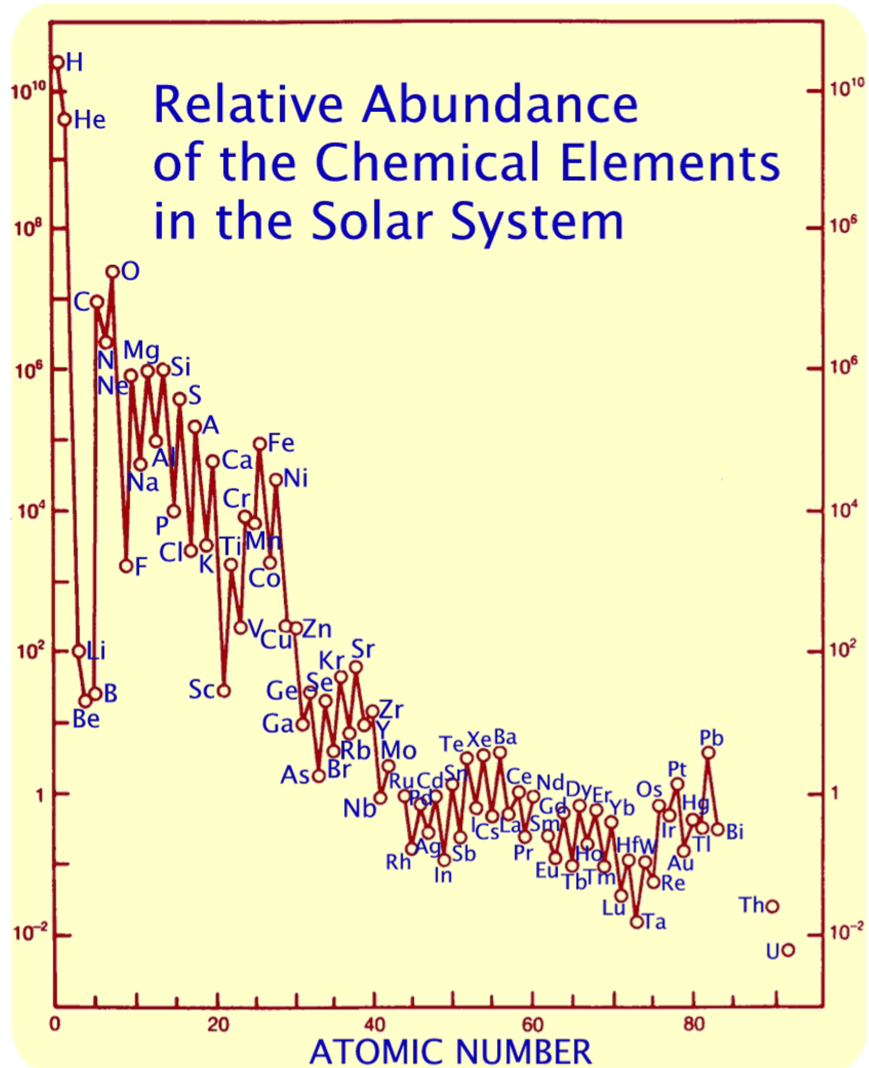
George Gamow

A Prelude

- Later, in 1953, Apher, Herman, and Follin greatly improved the predictions of nucleosynthesis in the hot universe (now usually called the *Big Bang Nucleosynthesis*).
- They found that the universe should contain about 25% of helium and 75% of hydrogen. To their surprise they found that no heavy elements were formed at all.

Layover: Cosmic composition

- Hydrogen: 74%
- Helium: 24%
- Oxygen: 1%
- Carbon: 0.5%
- Neon: 0.13%
- Iron: 0.1%
- Nitrogen: 0.1%
- Others: <0.05%

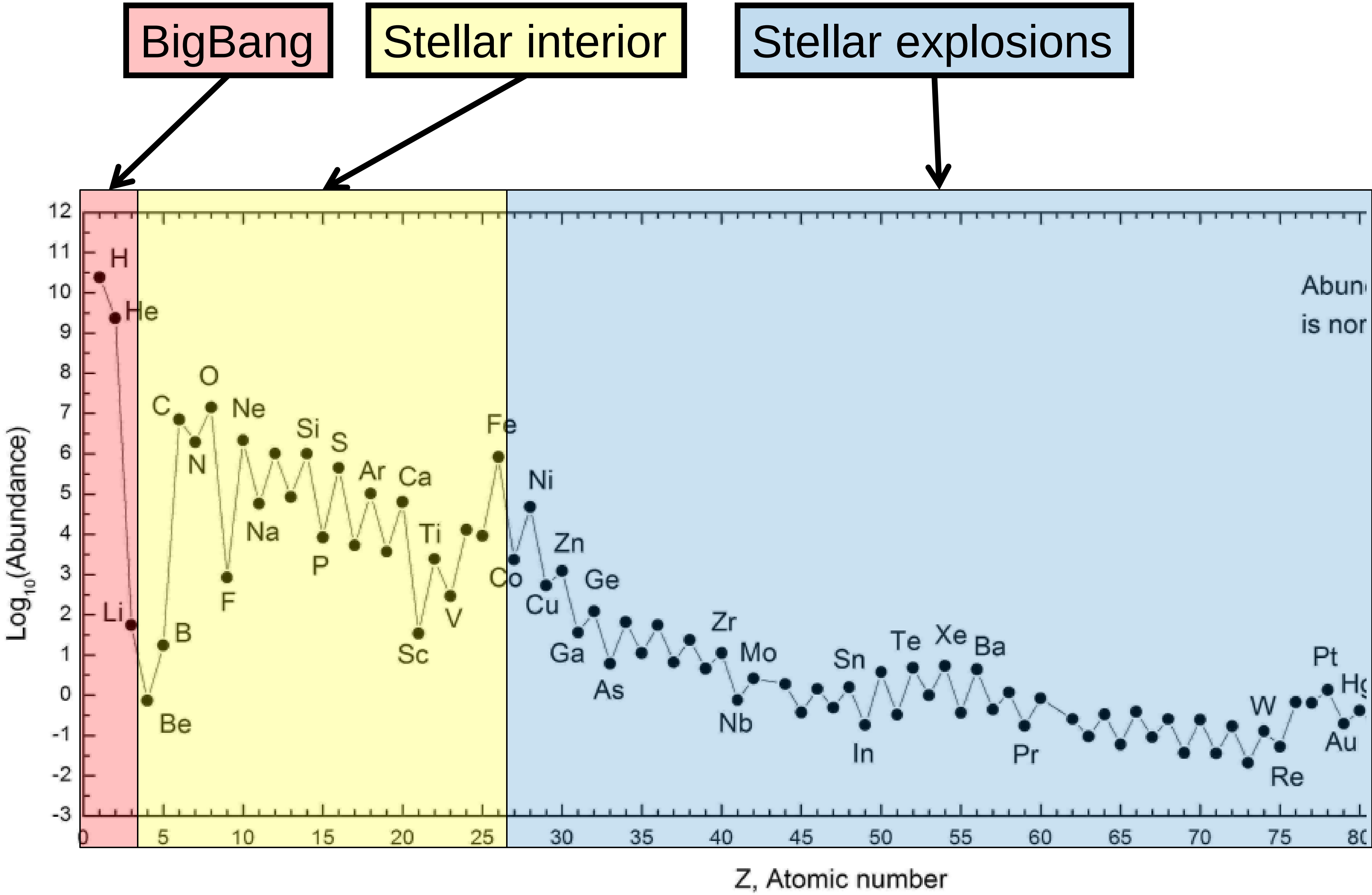


Origin of Chemical Elements

- For nuclear reactions to occur, the temperature must reach several million degrees Kelvin.
- Such temperatures occur naturally only in two cases:
  - Inside the stars (and during stellar explosions).
  - In the early universe about 3 mins after the Big Bang - that story is coming.

Stellar Nucleosynthesis

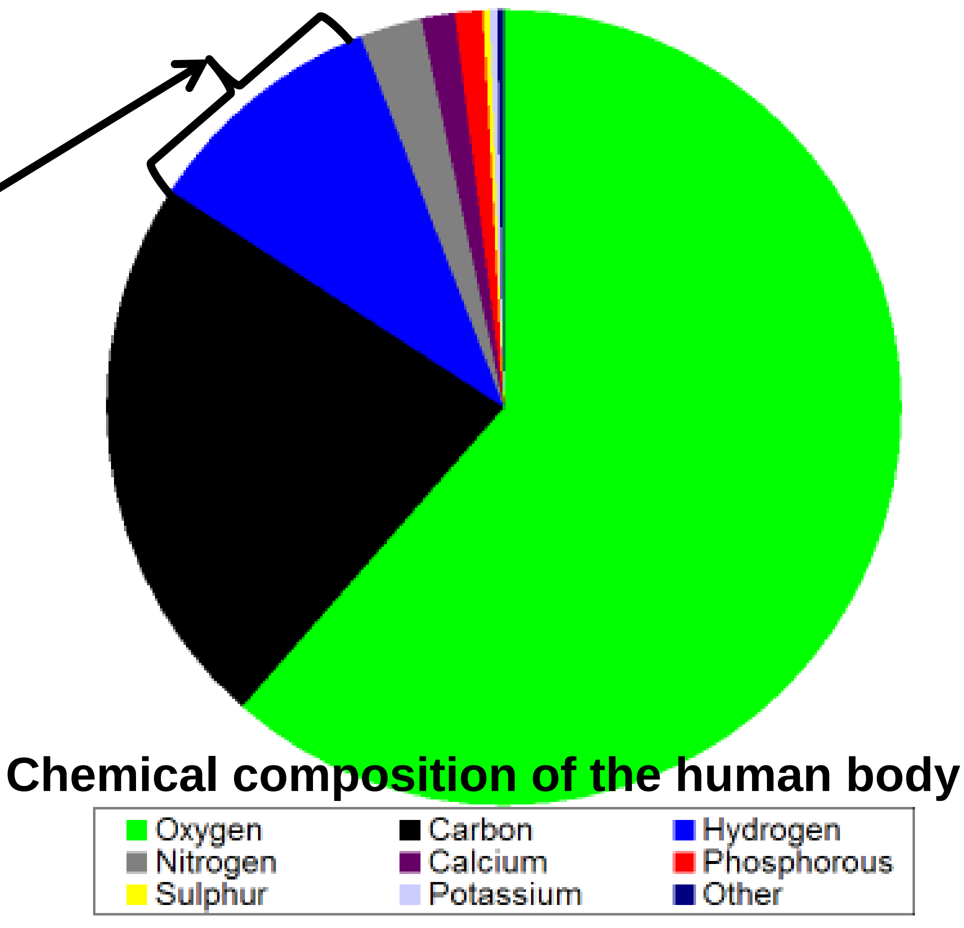
- Chemical elements heavier than Li are created in stars:
  - Elements below Fe are created in stellar interiors, during their normal lifetime.
  - Elements heavier than Fe are created in stellar explosions (novae and supernovae).
- We know that because calculation of stellar nucleosynthesis agree very well with observations.



BigBang
Stellar interior
Stellar explosions
Log10(Abundance)
Z, Atomic number
H
He
Li
Be
B
C
N
O
F
Ne
Na
Si
P
S
Ar
Ca
Sc
Ti
V
Fe
Co
Ni
Cu
Zn
Ga
Ge
As
Zr
Nb
Mo
Sn
In
Te
Xe
Ba
Pr
W
Re
Pt
Au

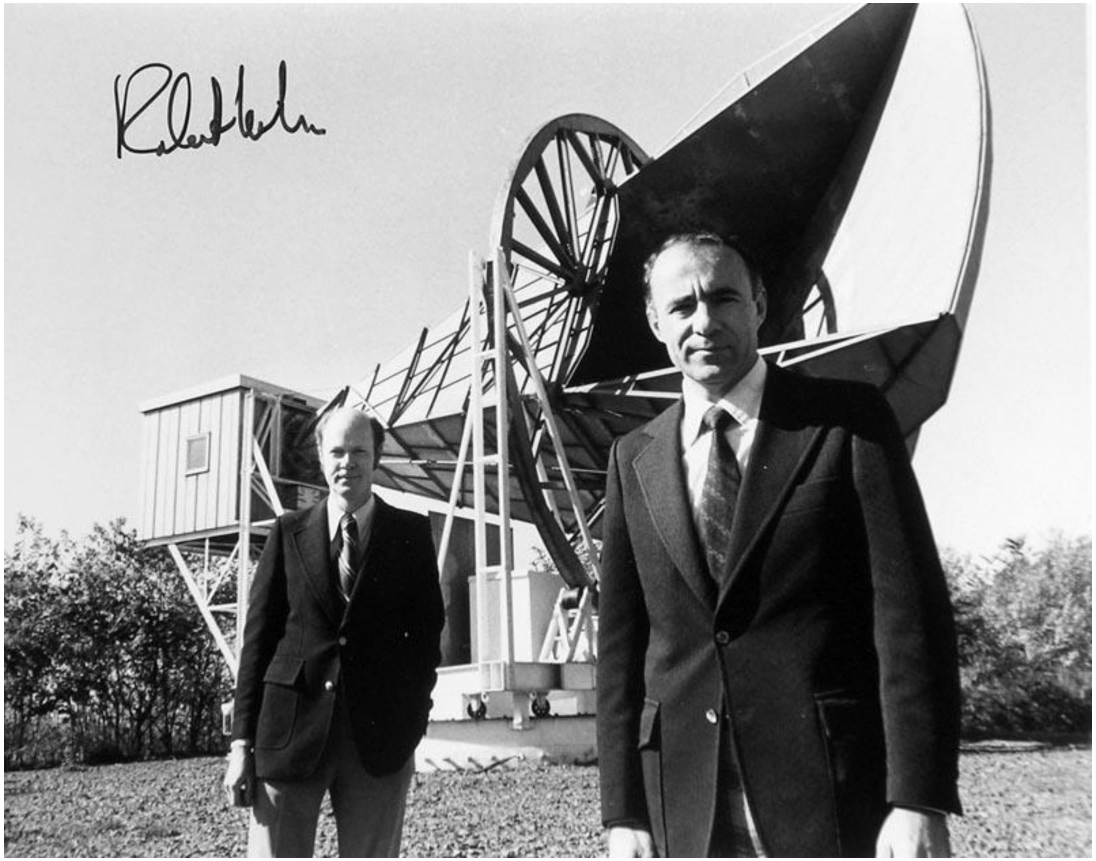
We Are the Star Stuff!!!

Only 10% of you is made in the Big Bang



Discovery of the CMB

- In 1964, Arno Penzias and Robert Wilson of Bell Labs were working on their new radio antenna...

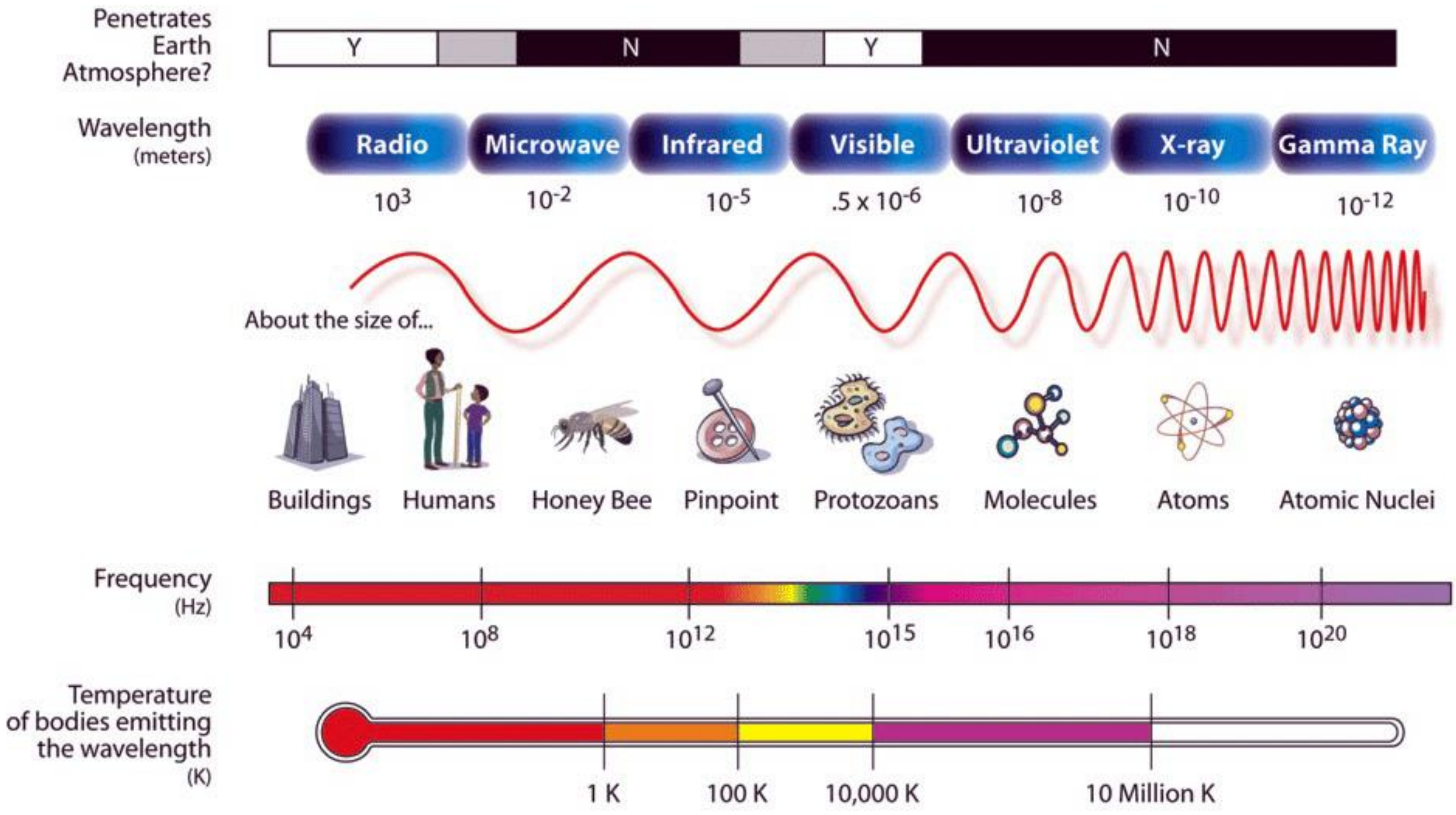


- They tried very hard to suppress the “noise” with temperature of about 3K that was coming from any direction on the sky.
- They failed, and thus made the most important discovery of modern cosmology: the **Cosmic Microwave Background**.
- At the same time Jim Peebles from Princeton University made a theoretical prediction that the universe must be filled with microwave radiation (the Alpher & Gamow work having been completely forgotten).
- Penzias and Wilson got the Novel prize for that discovery in 1978.

Meaning of the CMB

- The existence of CMB tells us that in the very beginning the universe was not only very dense, but also *very hot*, and most of the matter in the universe was in the form of hot gas.
- This gas emitted radiation, which redshifted into microwave range as the universe expanded.
- The CMB offers the best proof that the universe is highly (one part in 100,000) homogeneous on large scales.

Electromagnetic spectrum

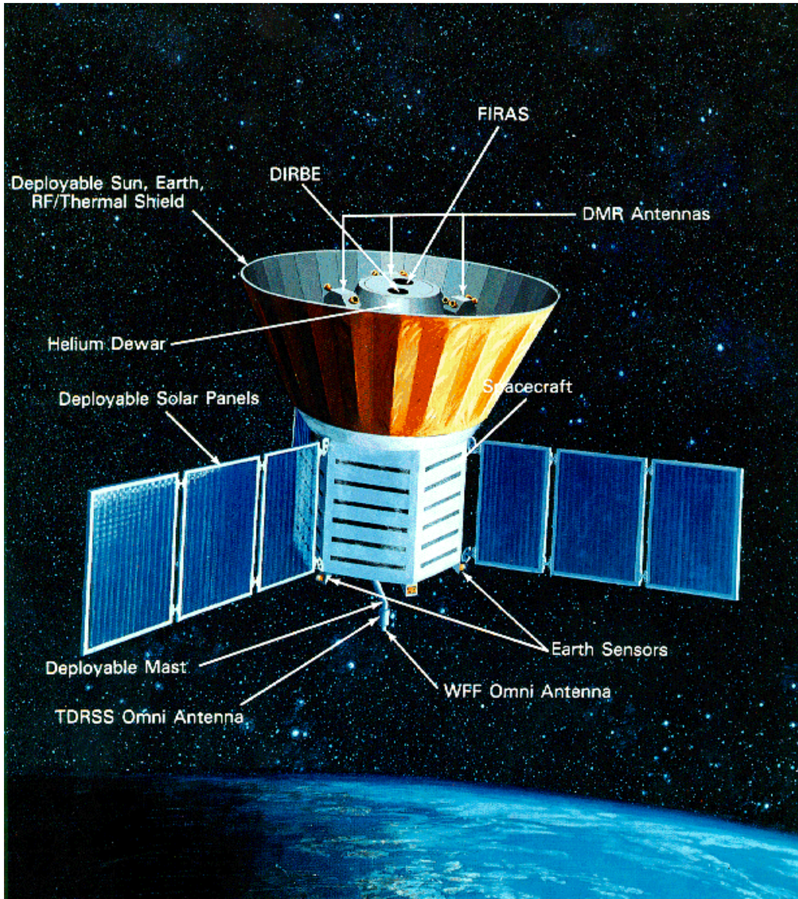


Observing CMB

- The discovery of the CMB was the most important development leading to the general acceptance of the Big Bang theory in mid 60s.
- However, for 30 years the progress in making measurements of the CMB were slow.
- The main challenge is the Earth atmosphere – what makes the atmosphere opaque to microwave radiation?
  A. Air
  B. Water vapor
  C. Carbon monoxide

COBE

- The study of the CMB was jump-started in 1989, with the launch of ***COBE*** satellite (COsmic Background Explorer).
- It worked for 4 years and was switched off in 1993.



COBE

- *COBE* studied several different kinds of cosmic backgrounds, but with respect to the CMB its mission was two-fold:
  - to measure very accurately the spectrum of the CMB.
  - to detect fluctuations (anisotropies) in the CMB.
- *COBE* performed both these missions brilliantly.

Spectrum of the CMB

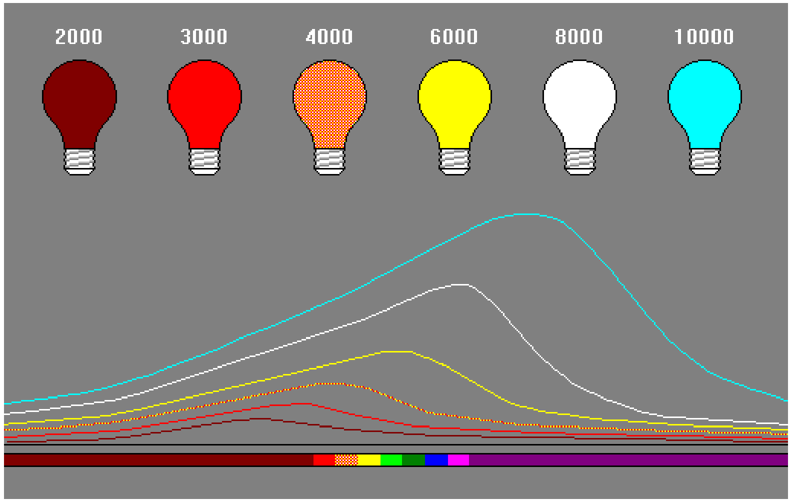
- Since the CMB is the remnant from the epoch when the universe was very hot and dense, it should have a so-called “black body”' spectrum.

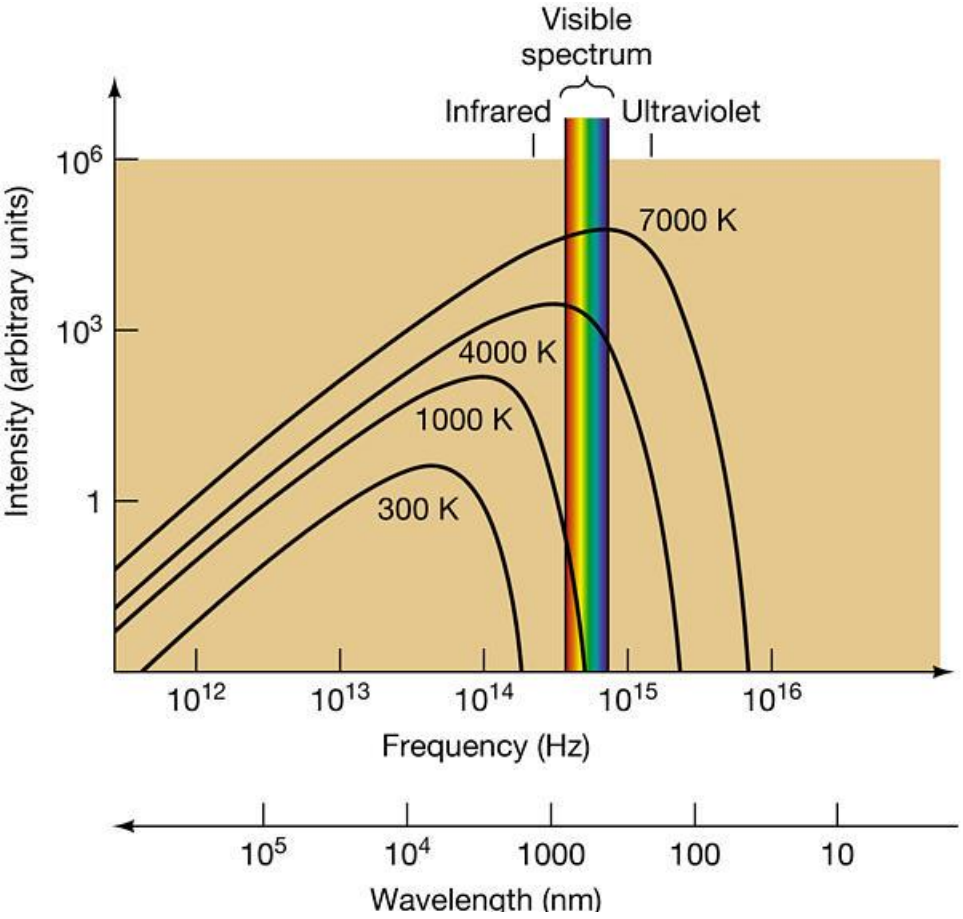
- This a (somewhat unfortunate) term scientists use to describe the radiation which was in the equilibrium with the gas it was emitted by.

- For example, solar radiation has a (nearly) black body spectrum, even if the Sun is not black at all.

“Black Body” spectrum

- The black body spectrum is characterized by a single number – its temperature.

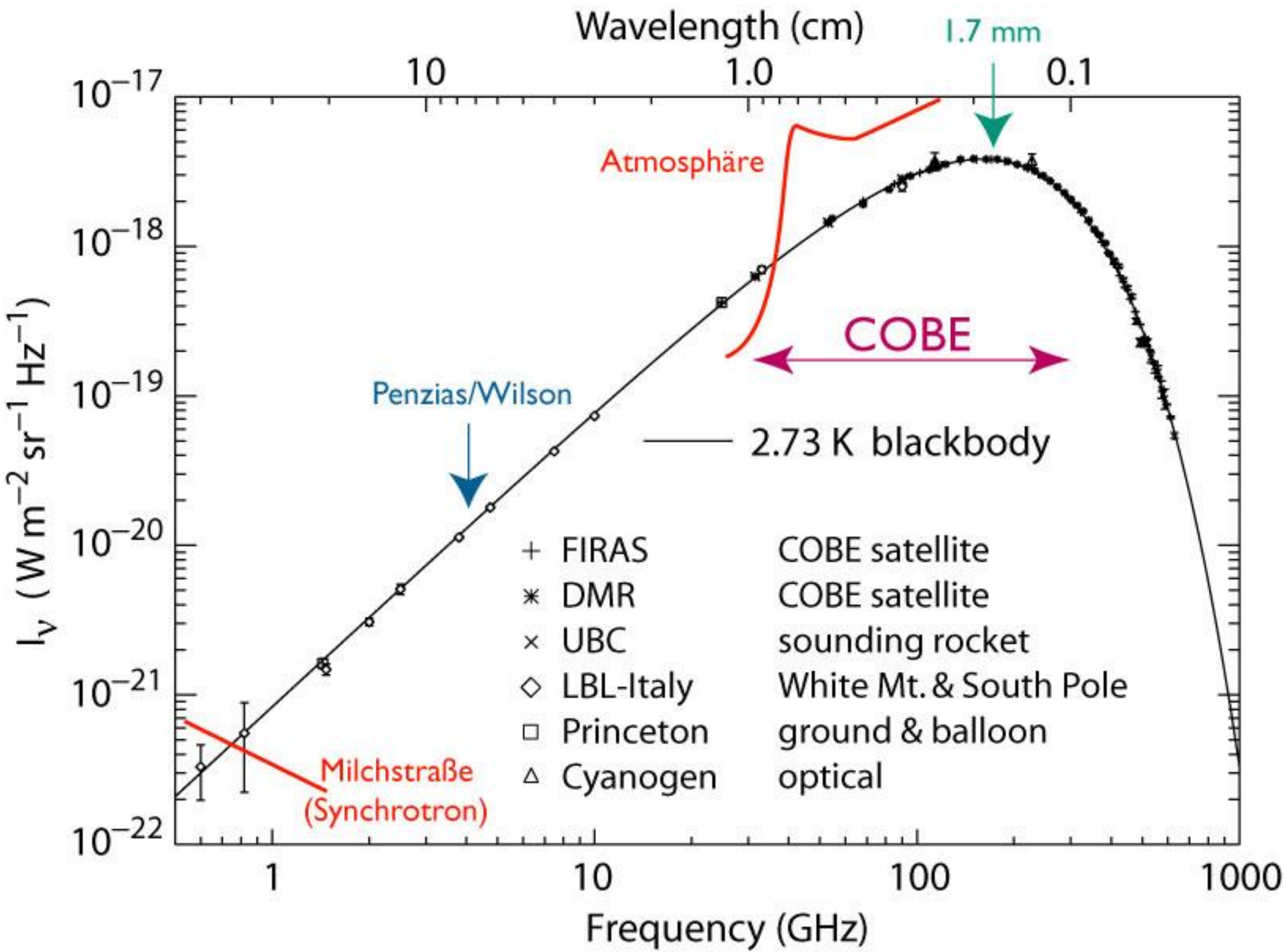




Spectrum of the CMB

- When the universe was dense and hot, everything was in the equilibrium then.
- Such an equilibrium is called "thermal equilibrium". Thus, the CMB should also have an equilibrium, black body spectrum.
- *COBE* was able to verify that to the accuracy of 1 part to 100,000! No other number in Astronomy is known to such a precision!
- *COBE* also measured the temperature of the CMB: $T_{\rm CMB} = 2.728 \pm 0.002\,{\rm K}$.

Spectrum of the CMB



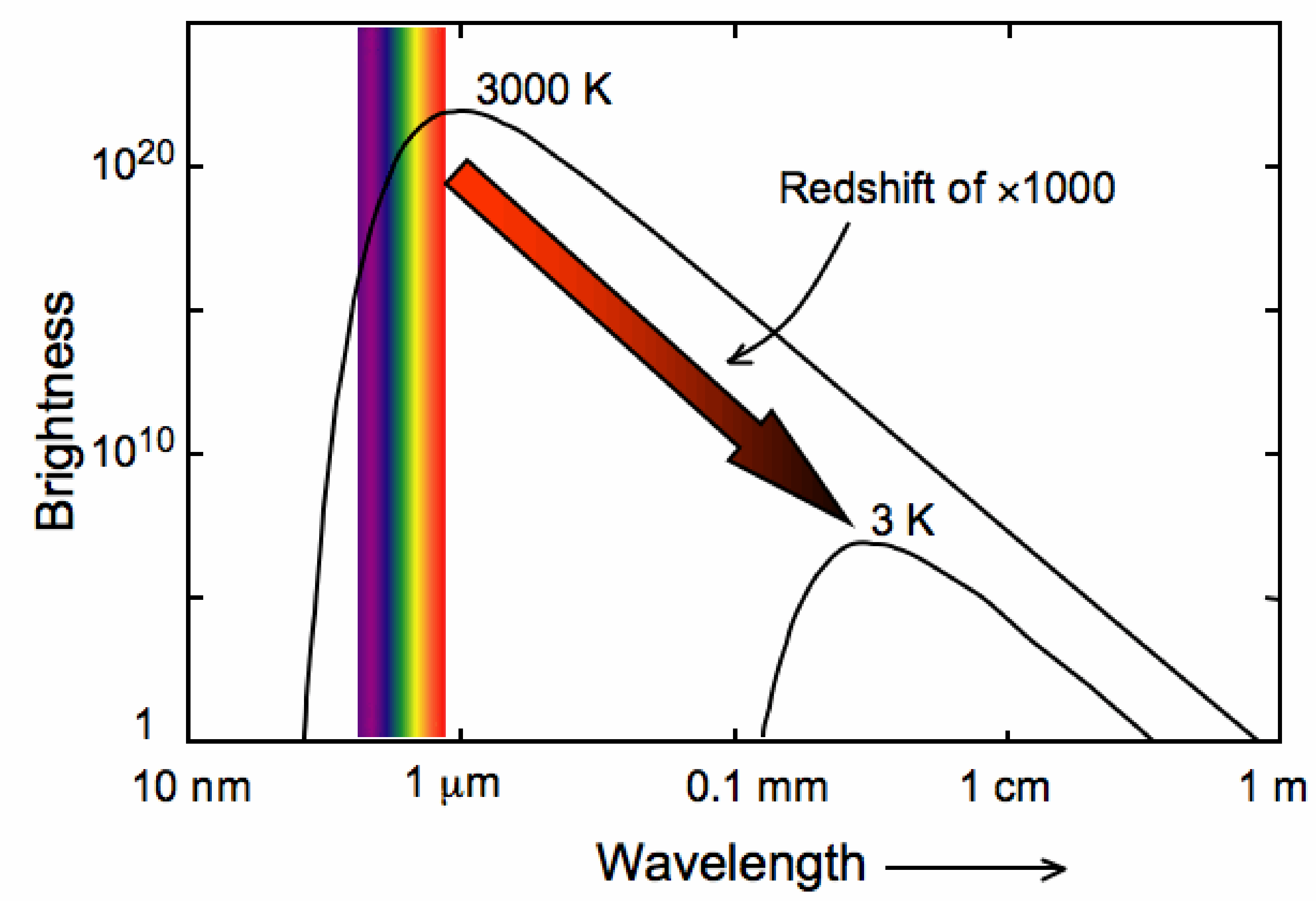
Evolution of CMB

- As the universe cools and expands, so does the CMB. Thus, in the past the CMB was ***hotter***. Quantitatively, the temperature of the CMB decreases in proportion to the scale factor, or, in terms in cosmological redshift z:

  $$T_{\mathrm{CMB}} = 2.73(1 + z)\,\mathrm{K}$$

- At z=3 the CMB temperature was
  A. 2.73 K
  B. 3*2.71 = 8.19 K
  C. 4*2.73 = 10.84 K
  D. -440 degree Fahrenheit

Evolution of CMB



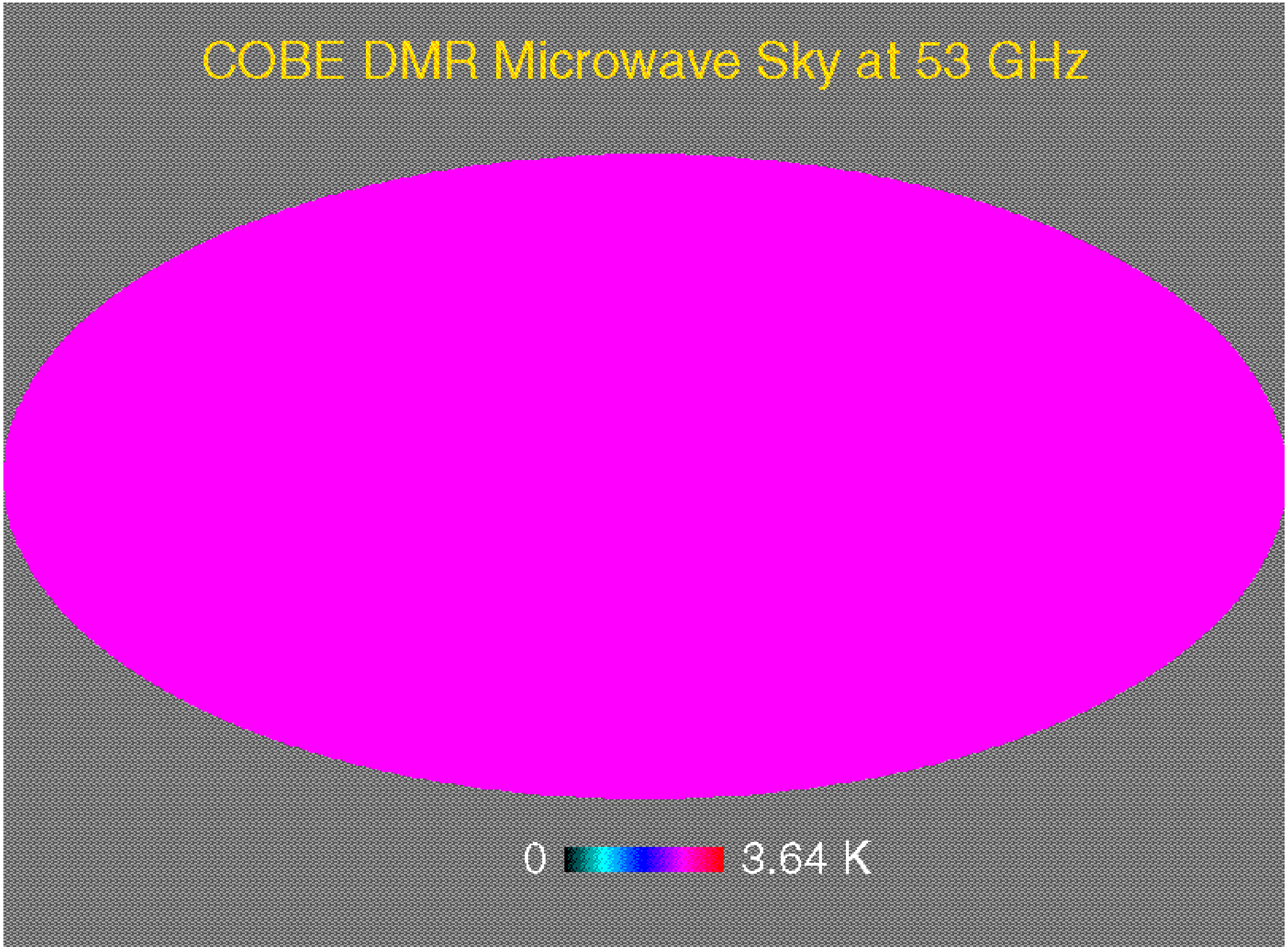
CMB Anisotropies

- The Big Bang theory also predicts that even if the CMB is highly homogeneous and isotropic, it is not 100% so, only 99.999%.
- There should be ***anisotropies*** in the CMB at a level of about 1 part in 100,000.
- Anisotropies in the CMB are sound waves passing through the cosmic gas when it was dense and hot. (Those sound waves are very very quiet, much quieter than any whisper you can hear).

CMB Anisotropies

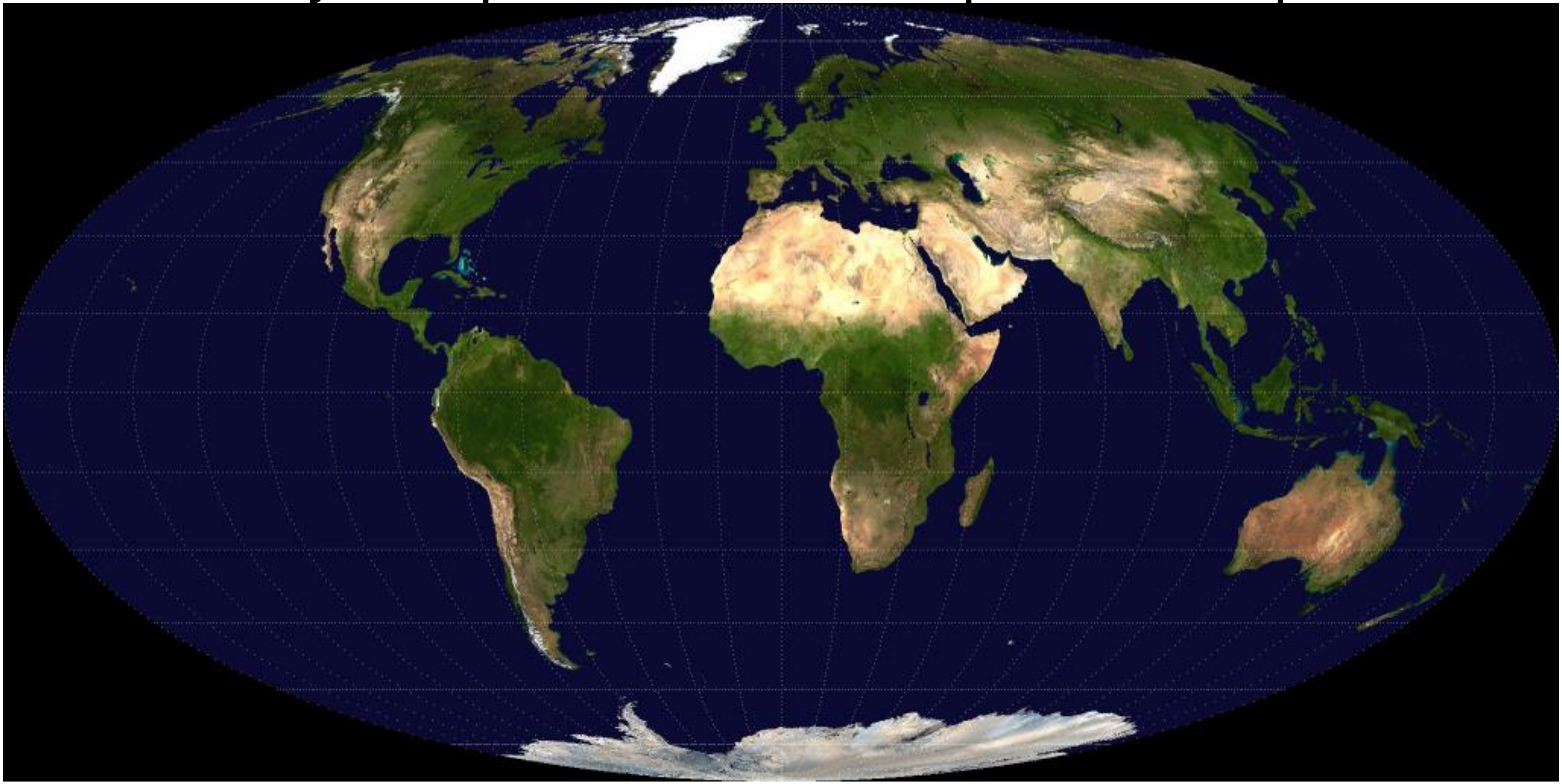
- *COBE* managed to detect these anisotropies and measure them very precisely.
- However, *COBE* “vision” was not very sharp, it was able to see only details with the size larger than 10 degrees on the sky. A human eye is 500 times better than that.
- Thus, *COBE* found the anisotropies (inhomogeneities), but did not tell much about them.

COBE Results

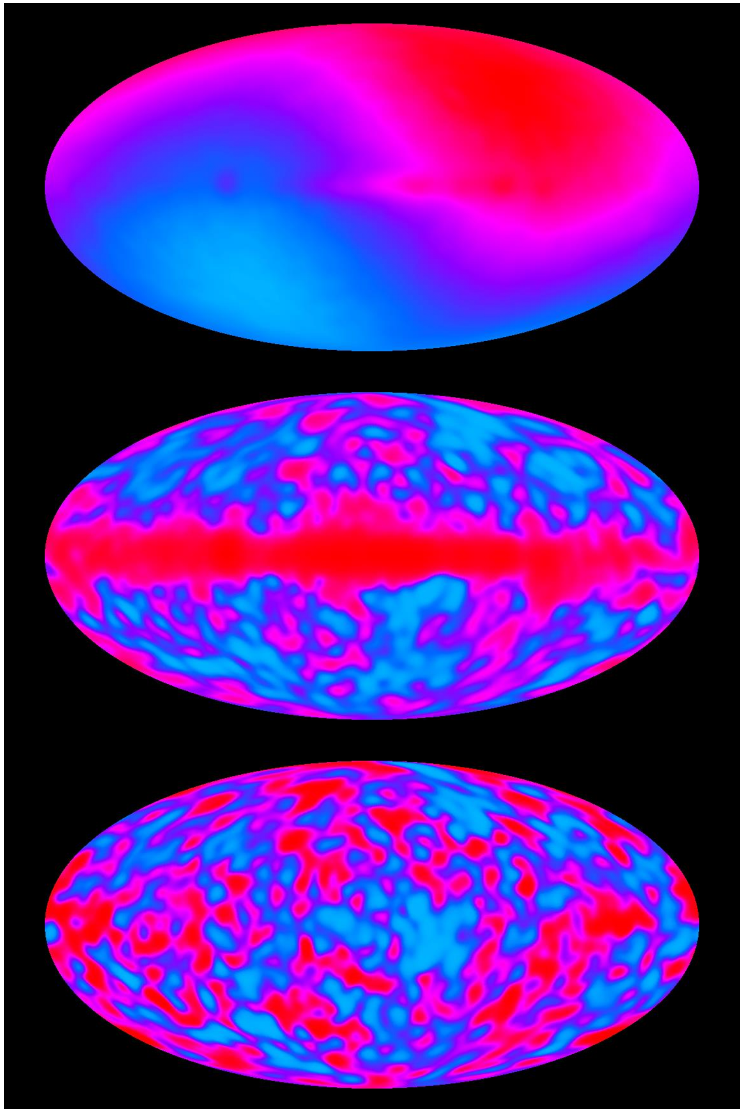


Mollweide Projection

- A way to represent a whole sphere on a plane.



COBE Results



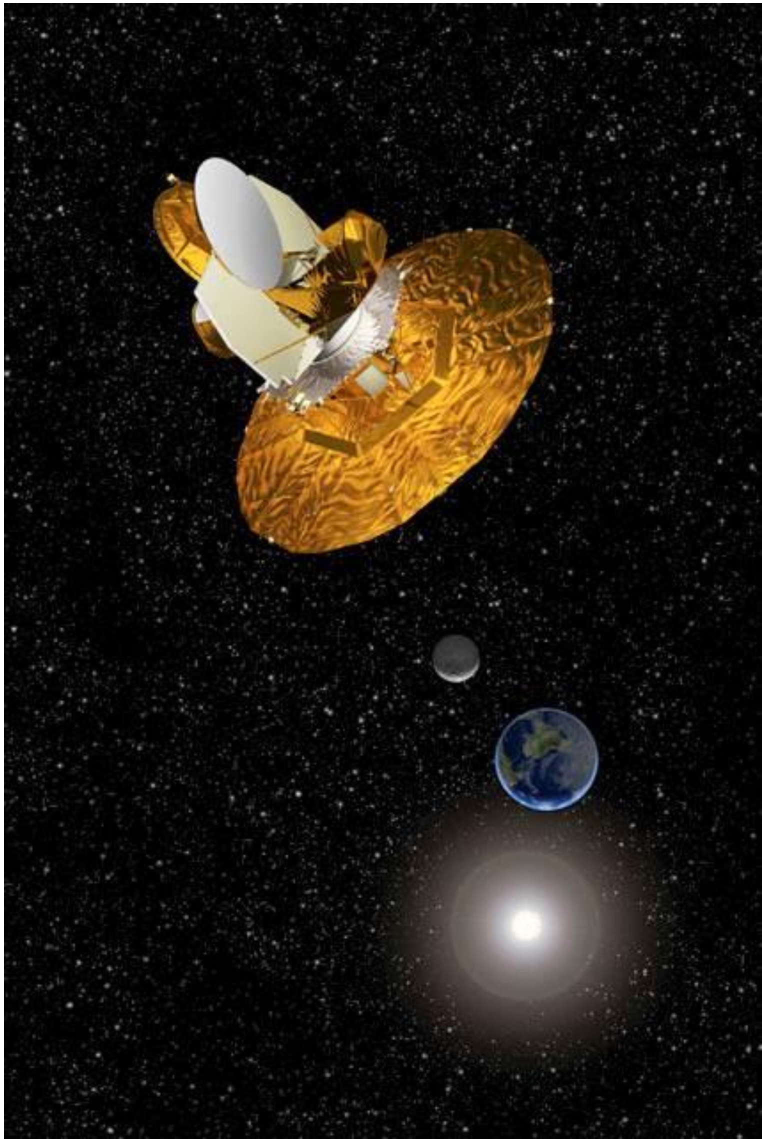
Isotropic background removed

Doppler effect removed

Milky Way galaxy removed

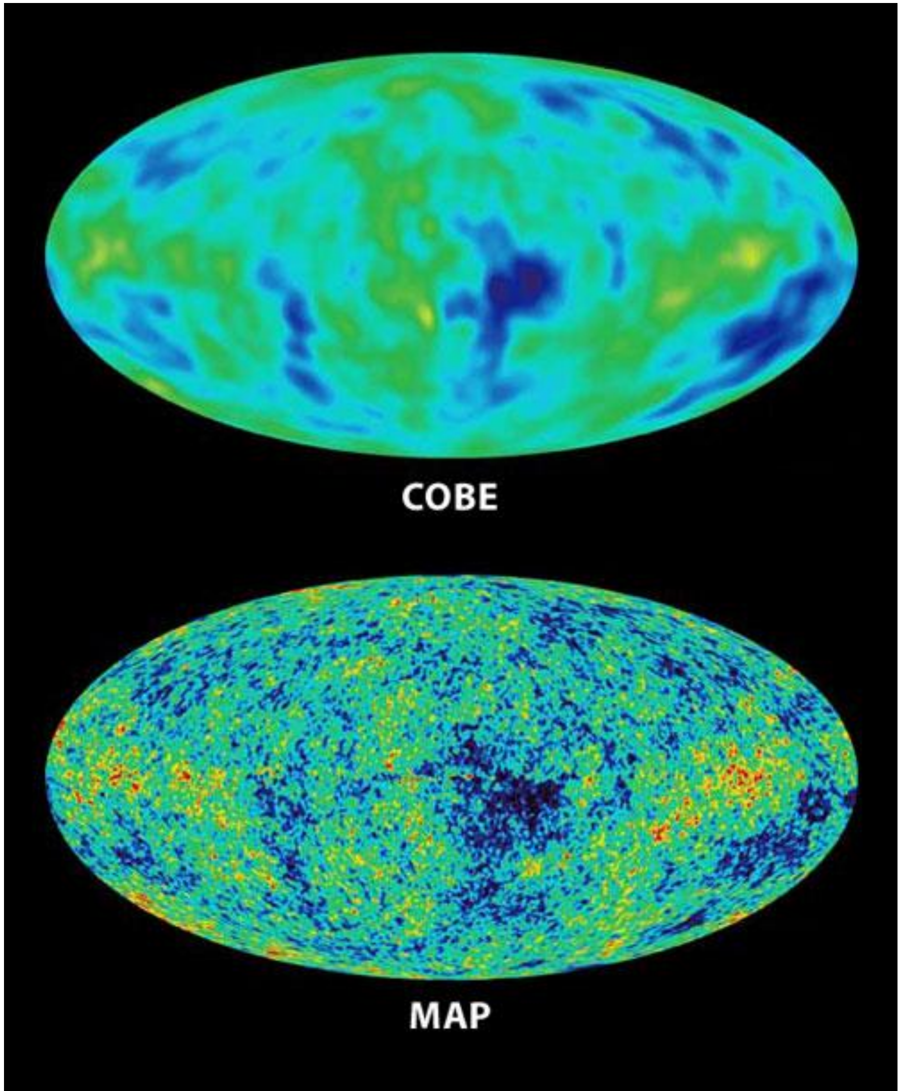
WMAP

- In June 2001 another satellite was launched, called MAP (Microwave Anisotropy Probe). The leading scientist on the project was David Wilkinson from Princeton University. David suddenly died in October 2002, and MAP mission was renamed WMAP (Wilkinson Microwave Anisotropy Probe) in his honor.



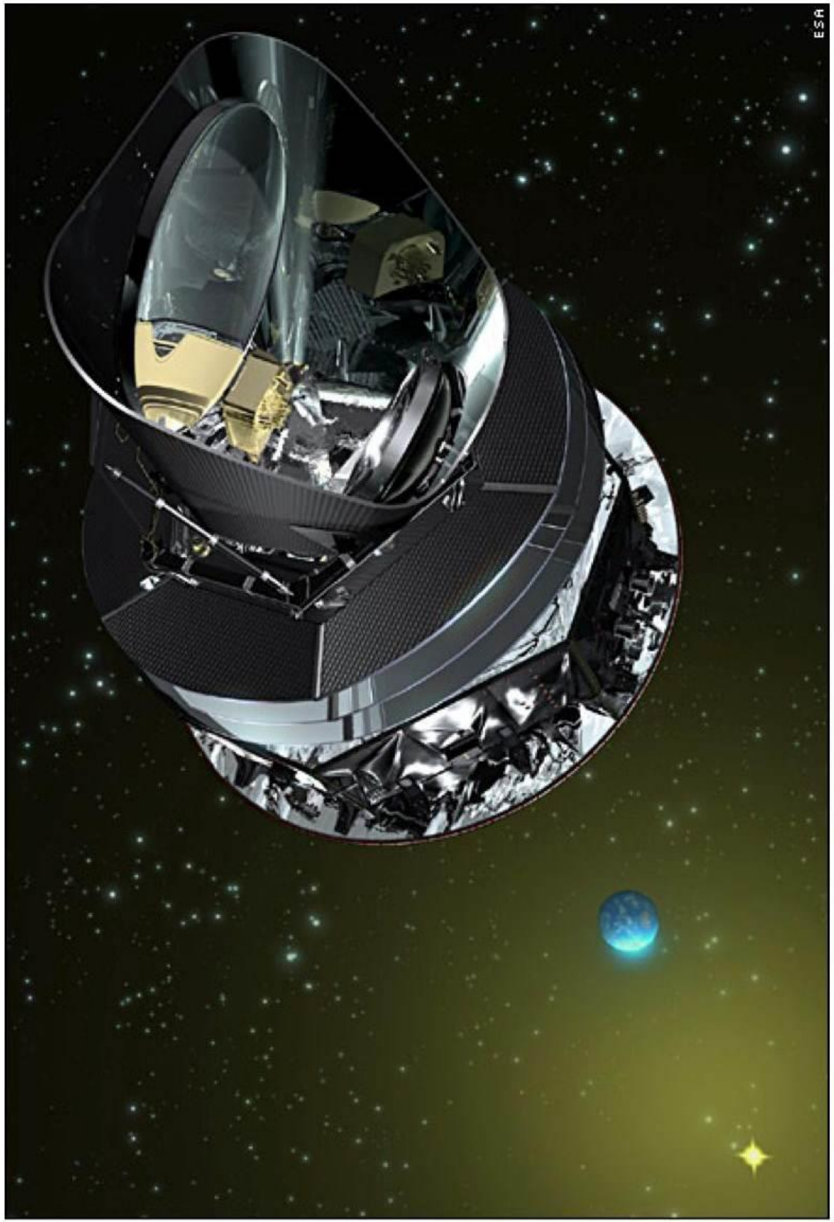
WMAP

- WMAP operated for 9 years, being extended twice – it was so successful.
- Its “vision” was 10 times sharper than COBE’s.

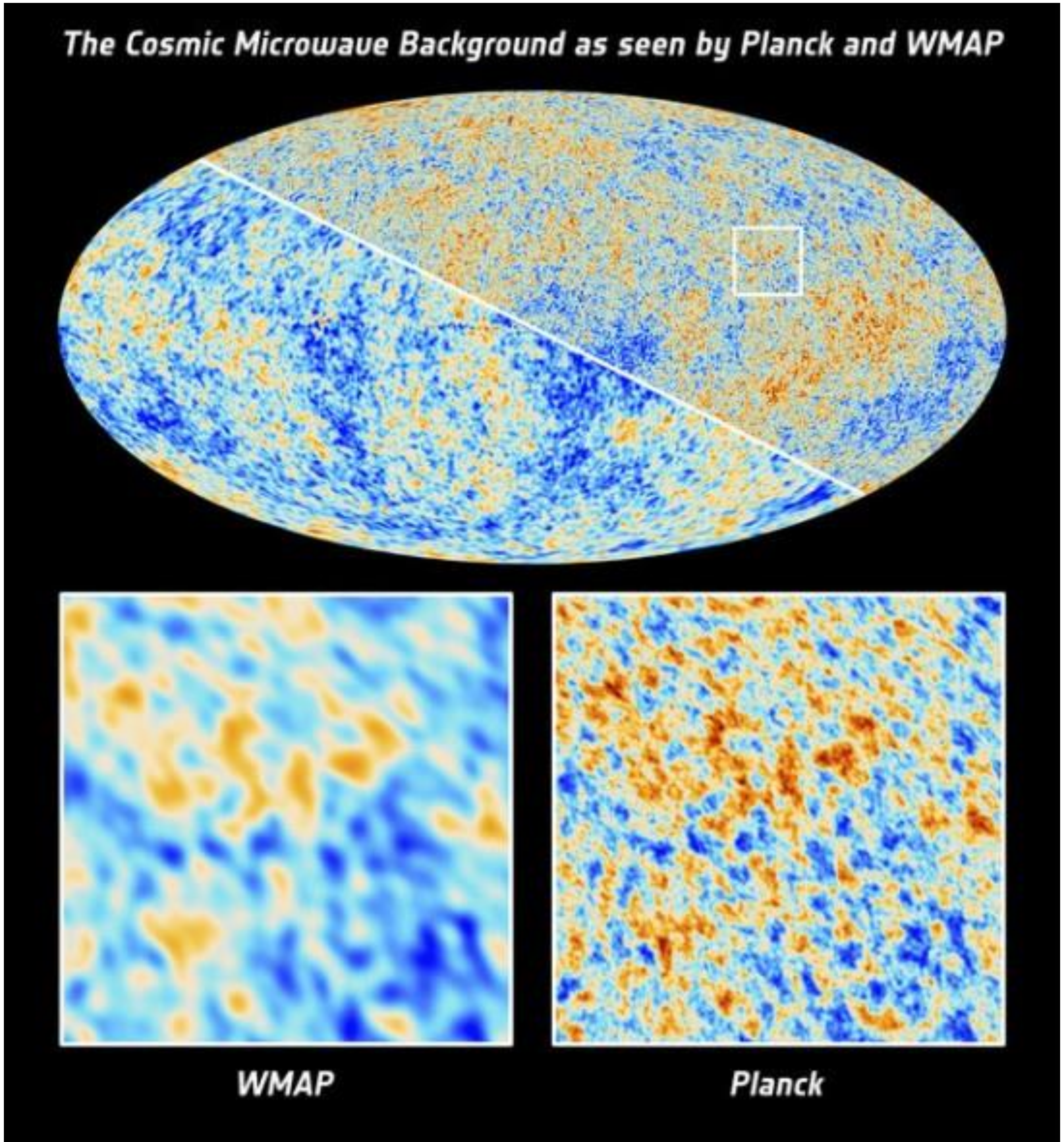


Planck

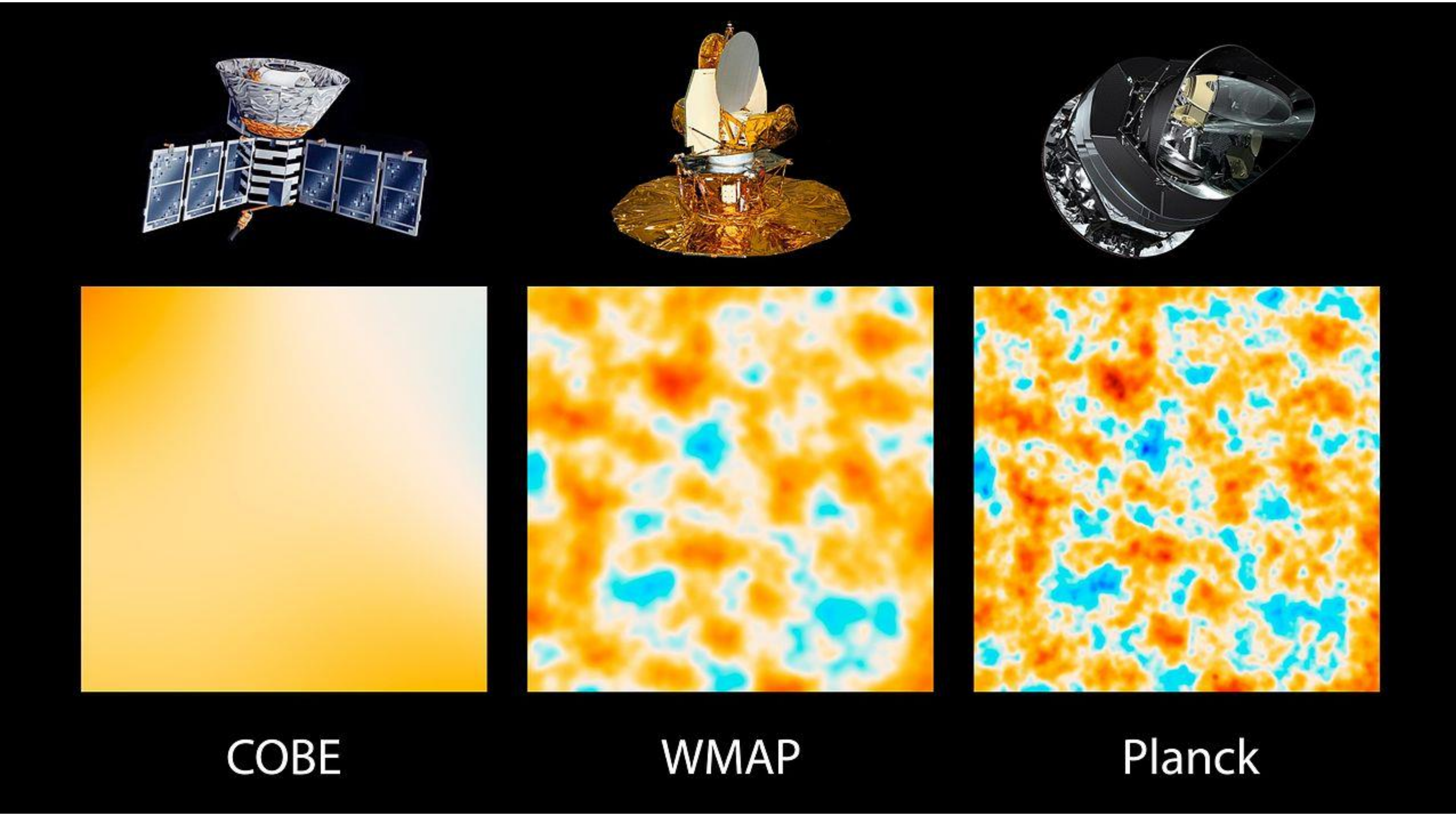
- Planck satellite was launched by ESA in May 2009 and operated until the end of 2011.
- Its “vision” was 5 times better than WMAP.



Planck and WMAP

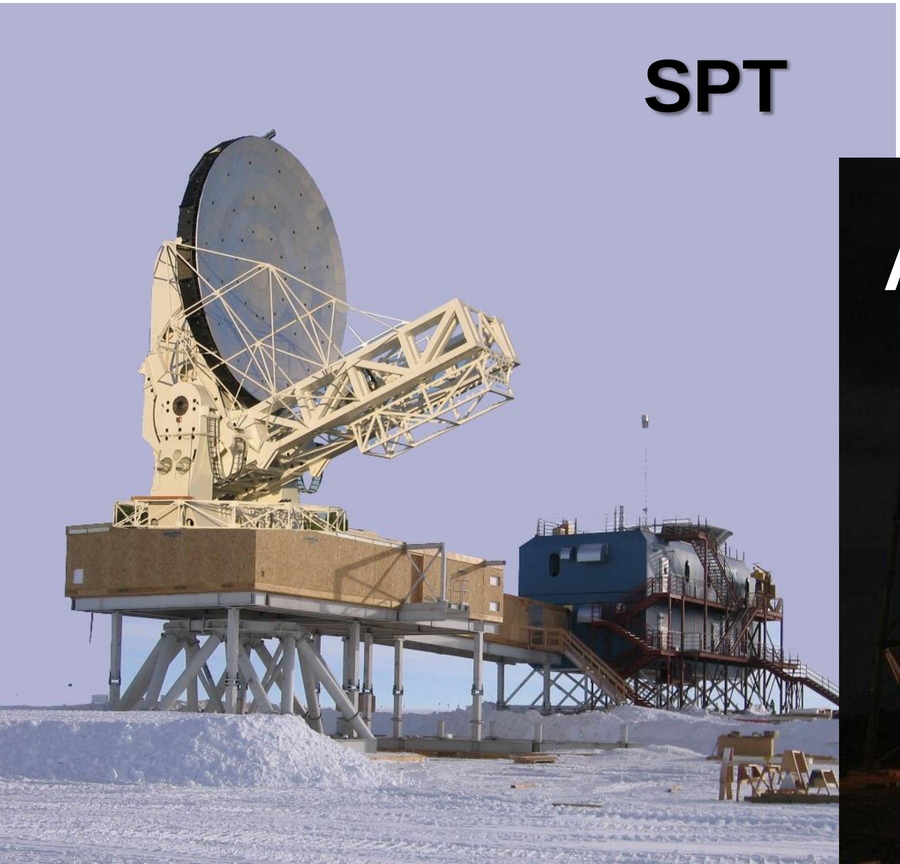


Space Missions



Measurements from the Ground

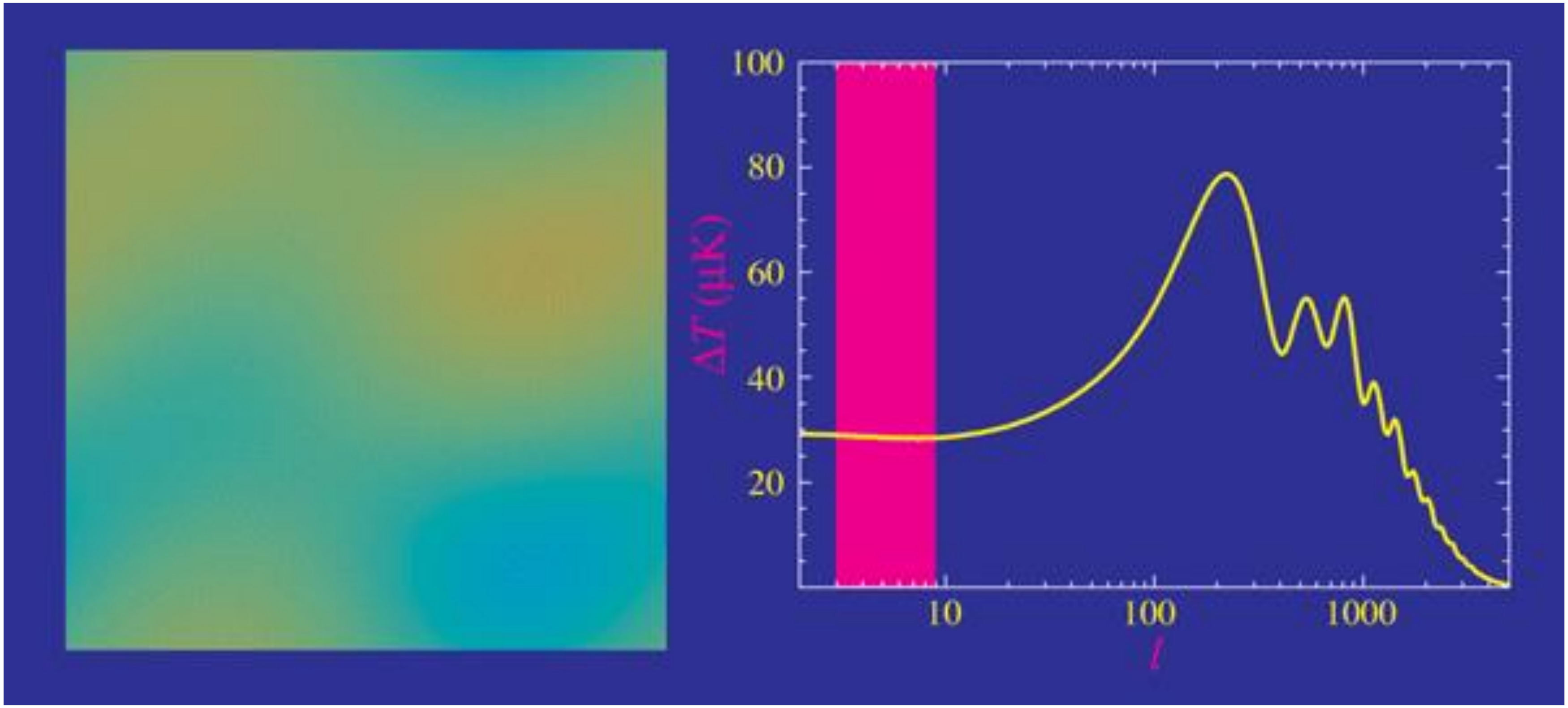
- There were more than a dozen various ground- and balloon-based experiments.



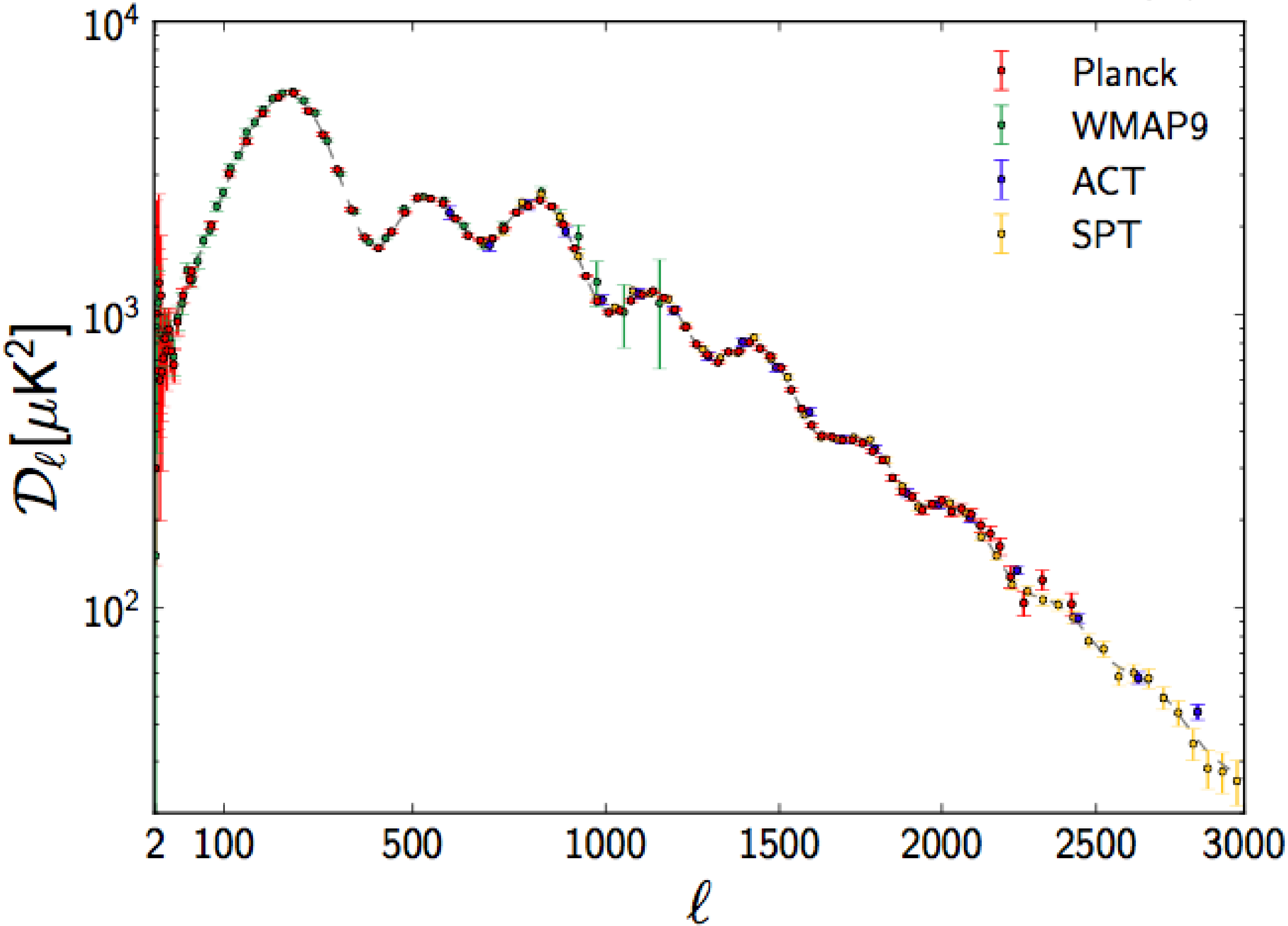
CMB Angular Spectrum

- The anisotropies are usually studied by measuring their *angular spectrum* (not to be confused with the *frequency spectrum*).
- The spectrum of anisotropies tells us how the power in a given sound wave changes with the wavelength. On the sky, wavelengths are measured in ***multipoles*** ℓ: $\ell = 0$ is the whole sky, $\ell = 1$ is half the sky, $\ell = 2$ is quarter of the sky, $\ell = 3$ is one-sixth of the sky etc.

CMB Angular Spectrum



Era of “Precision Cosmology”



Why Should We Study the CMB?

- The CMB is not only of interest by itself, hidden in its spectrum is the information about the universe we live in.
- In other words, the spectrum of the CMB contains in the encoded form the values of all the cosmological parameters: H_0, Ω_M, Ω_Λ, and some others.
- You can thing about the spectrum of anisotropies as a fingerprint of the Universe!

CMB Anisotropies and Galaxies

- So, there are tiny ripples on the CMB. Surprisingly, there ripples have the direct connection to the galaxies that surround us today.
- Since the CMB was emitted long time ago, small inhomogeneities in the universe on small enough scales had a long time to grow. By our time they grew so much as to become galaxies, clusters of galaxies, and large-scale structure (super-clusters).
- Thus, the ripples in the CMB are the *direct ancestors* of galaxies!

CMB Anisotropies and Galaxies

If the CMB was perfectly smooth, we wouldn't be here!!!